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Earth and Space Data Computing Division

Earth Sciences Directorate, Goddard Space Flight Center

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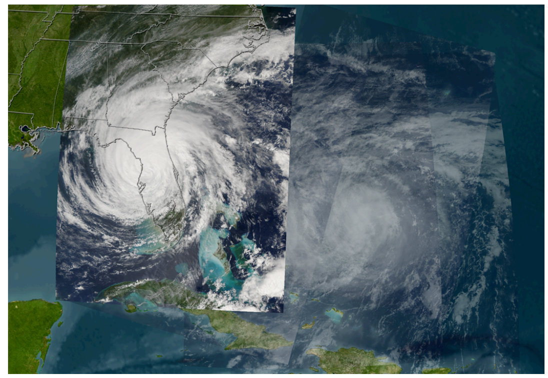
Scientific Visualization Studio

2004 North Atlantic Hurricane Season Showcases SVS Capability and Expedience

With the close of summer, most people's thoughts turn to the beginning of a new school year, fall's vibrant foliage, or Monday Night Football. But for many people at GSFC, the end of summer marks the beginning of another season entirely—hurricane season. For the staff of ESDCD's Scientific Visualization Studio (SVS), the 2004 North Atlantic season has been one for the records, with tens of millions of viewers seeing their work.

The 2004 North Atlantic season began in early August with Hurricane Alex brushing

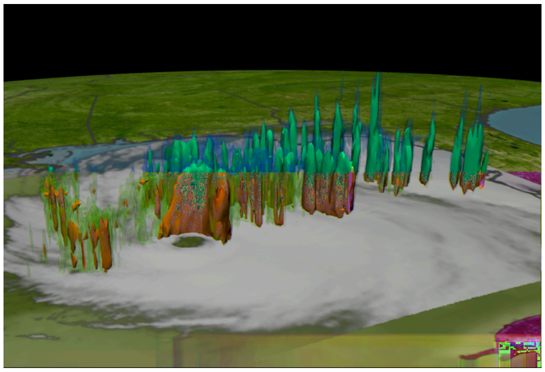


Hurricane Jeanne, September 26, 2004, as observed by the Aqua satellite (Animator: Stuart Snodgrass, GST/Applied Information Sciences Branch).

the Outer Banks of North Carolina. A week later, Hurricane Charley, the first of the "Florida Four," slammed Cuba and continued on to hit Florida as a Category 4 storm. Following in rapid succession over the next five weeks were hurricanes Frances, Ivan, and Jeanne—each storm causing devastation to islands in the Caribbean and continuing on to Florida. Not since 1886, when Texas was also struck four times, has one state taken so many direct hits.

With this highly unusual storm activity came an unprecedented interest in GSFC's hurricane expertise. Everybody wanted to know about hurricanes, and everybody wanted to know about them fast. That is where the SVS's rapid turnaround capabilities came into play.

"This year's hurricane season has been the busiest ever for the SVS," says Stuart Snodgrass of GST in the Applied Information Sciences Branch. "It was almost like the hurricanes were on a conveyor belt. No sooner had I finished one animation with the latest data set, another would be waiting in the wings."



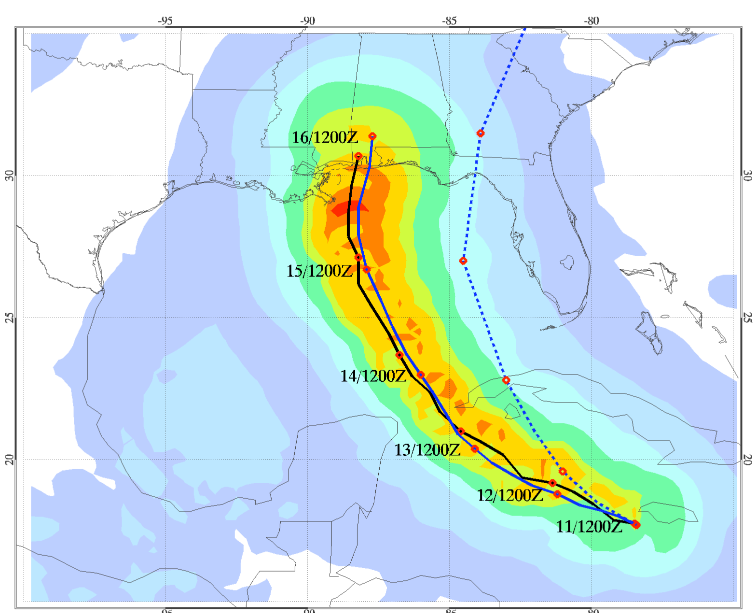
TRMM looks at the rain fueling Hurricane Ivan on September 15, 2004. Blue represents areas with at least 0.25 inches of rain per hour. Green shows at least 0.5 inches of rain per hour. High vertical bands on the outside of the storm indicated that Hurricane Ivan was very likely to spawn tornados in Florida and Georgia (Animators: Lori Perkins and Greg Shirah, GSFC/Applied Information Sciences Branch).

The SVS provided daily support to GSFC TV media coverage including numerous breaking news visualizations featuring current data from the perspective of TRMM, Aqua, Terra, SeaWiFS, GOES, and other spacecraft. With the SVS's ability to turn many of these visualizations around in a matter of hours (vital for breaking news stories), NASA products were showcased through wide media exposure. GSFC scientists including Marshall Shepherd (Mesoscale Atmospheric Processes Branch) and Jeff Halverson (Mesoscale Atmospheric Processes Branch/UMBC) used SVS visuals to support many live interviews. These interviews and visuals were shown on national television shows, including NBC's Today Show, NBC Nightly News; and CNN's Larry King Live, Lou Dobbs Tonight, and Wolf Blitzer Reports. Additionally, over 40 live interviews on local news broadcasts (many in top-10 media markets) featured SVS visualizations.

http://svs.gsfc.nasa.gov

fvGCM Group Teams with SVS to Visualize Early and Accurate Hurricane Forecasts

A recent high-resolution (~25 km) numerical weather prediction (NWP) application of the NASA finite-volume general circulation model (fvGCM) has been producing valuable real-time weather information targeted toward improving hurricane formation, track, and intensity forecasts. The twice-daily experimental NWP forecasts have been running on one 512-CPU node of Columbia, an



Hurricane Ivan's track and intensity as forecasted by the NASA fvGCM 5 days before landfall (solid black line), initialized at 12Z on September 11, 2004. The forecasted track and maximum sustained wind speeds (dark orange represents winds in excess of 114 knots and a Category 4 hurricane on the Saffir-Simpson Scale) are compared with the official National Hurricane Center (NHC) forecast (dashed blue line) issued at 12Z on September 11, 2004, and the NHC observed positions (solid blue line) (Image credit: William M. Putman, NASA/GSFC).

SGI Altix at NASA Ames Supercomputing Division (NAS), producing real-time forecasts throughout the 2004 hurricane season.

Members of the fvGCM modeling group, under the direction of Dr. Robert Atlas of the Laboratory for Atmospheres at NASA/GSFC, have begun to assess the model's accuracy in predicting landfall of hurricanes up to 5 days in advance. Results for hurricanes Frances, Ivan, and Jeanne have been promising, demonstrating accuracy in predicted landfall on the order of 100 km 3 to 5 days in advance. The fvGCM has been successful at capturing the intensity of these storms. Most notably the 5-day forecast for Hurricane Ivan accurately predicted intensification to a strong Category 4 hurricane on the Saffir-Simpson scale, ultimately making landfall on the Gulf coast of Alabama as an intense Category 3 storm consistent with observations from the National Hurricane Center.

The fvGCM modeling group has teamed up with ESDCD's Scientific Visualization Studio (SVS) to produce high-quality visualizations of the fvGCM forecasts. The SVS has produced visualizations of the modeled hurricanes, comparing their observed and predicted tracks, and has also produced high-quality global views demonstrating the dramatic scale of this high-resolution global model. Work is underway to produce 3-dimensional visualizations, allowing scientists to see into the complex structure of these hurricanes as modeled by the fvGCM.

The fvGCM was ported, tested, and integrated on Columbia by Bo-Wen Shen of Science Applications International Corporation with the assistance of support staff at NAS and the NASA Center for Computational Sciences (NCCS) at GSFC. Recent performance optimizations of the fvGCM on Columbia by William Putman of the NCCS have led to a substantial increase in the overall throughput of the NWP application on the order of 35 to 40 percent.

http://fvnwp.gsfc.nasa.gov/

Computational Technologies Project

New Framework Confronts a Monster Space Weather Event

Covering the whole physics from the Sun to the Earth, a new simulation tool is being applied to the biggest solar event in recent history, a month-long series of outbursts dubbed the "Halloween 2003 space storms." This Space Weather Modeling Framework (SWMF) is the product of a Computational Technologies (CT) investigation at the University of Michigan.

"With the help of the CT Project, we just delivered our last major milestone, which is a fully operational framework with nine models working together," said SWMF principal investigator Tamas Gombosi, who is chair and professor of the Department of Atmospheric, Oceanic, and Space Sciences at Michigan. "This is the first time that we have exercised this brand new tool for a very challenging major event. It is a fortunate combination of simulation advances and the Sun cooperating in a very exciting way."

SWMF has its origins in Michigan's BATS-R-US code developed under the CT Project (then known as the Earth and Space Sciences Project) beginning in 1996. Many of the SWMF models are considered world-class, Gombosi said, "but coupled together, they are better than the sum of their parts." The current SWMF links 9 models to represent the complex physics of space weather:

- A Solar Coronal model (SC) represents the Sun's corona (atmosphere) using solar observation data.
- An Eruptive Events Generator (EE) inputs a coronal mass ejection (CME) into the initial conditions of the simulation. The CME then propagates outward

through the SC and Inner Heliosphere models self-consistently.

- A Solar-energetic Particles model (SP) describes the transport, acceleration, and scattering of these particles from the solar event to the Earth's atmosphere.

- An Inner Heliosphere model (IH) simulates the solar wind from the outer boundary of the corona (SC) to the Earth's magnetosphere and beyond, based on magnetohydrodynamics (MHD).

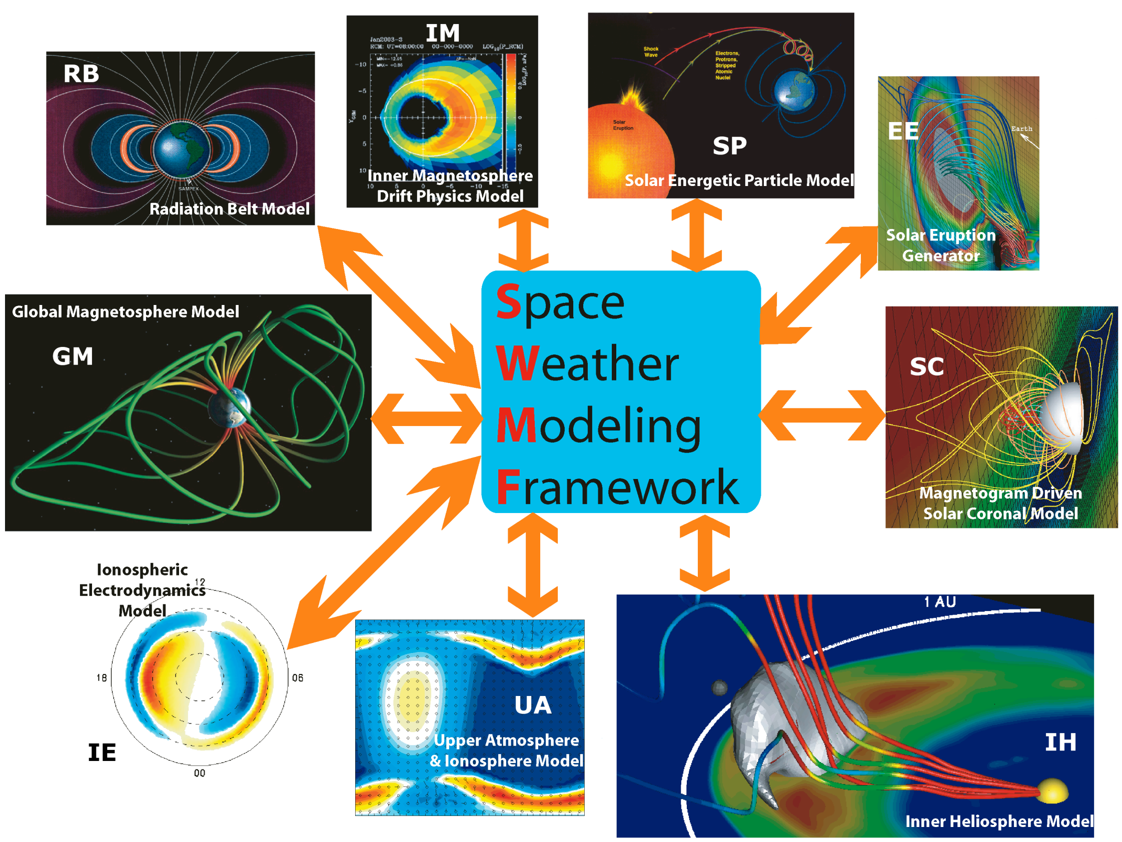
- A Global Magnetosphere model (GM) describes the connection between the inner heliosphere and the outer portion of the Earth's magnetosphere, based on MHD.

- A Radiation Belt model (RB) tracks trapped particles.

- An Inner Magnetosphere model (IM) calculates the dynamic behavior of particles and the electric fields and currents in the Earth's inner magnetosphere and computes their effects on the inner magnetosphere and upper atmosphere.

- An Upper Atmosphere model (UA) simulates the dynamics of the Earth's thermosphere and ionosphere.

- An Ionospheric Electrodynamics model (IE) calculates the electric potential in the Earth's ionosphere.

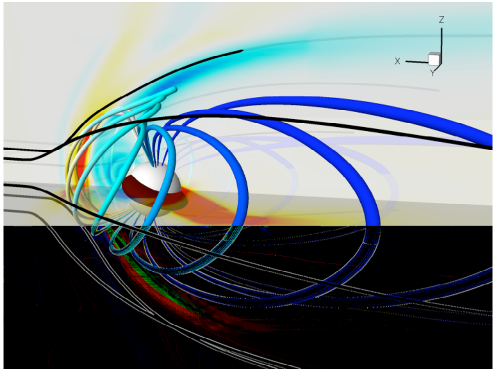


The Space Weather Modeling Framework (SWMF) couples 9 models to simulate the physics from the Sun to the Earth (Image credit: Darren De Zeeuw, University of Michigan).

The Halloween 2003 storms are the first real application of the complete SWMF. “There were several unique features, which is why it is very important to exercise simulation tools,” Gombosi said. Beginning in late October and lasting through early November, three sunspots, including one the size of Jupiter, launched a series of solar eruptions. Among the 60 solar flares was the most massive ever observed, an X-28 flare accompanied by a CME on November 4. The Sun spewed out several billion tons of matter at an astonishing 8 million kilometers per hour. Although this blob of charged gas did not hit Earth, geomagnetic storms resulting from multiple Earth-bound flares and CMEs had widespread effects: Two satellites were knocked out of commission, and 28 more were damaged. Airlines diverted their planes. Sweden suffered a power outage. Astronauts on the International Space Station had to take cover several times. The Northern Lights reached as far south as Florida.

The Michigan team’s Halloween 2003 simulation is a monster in its own right. “This is the biggest simulation we have done,” Gombosi stressed. “No one has ever attempted such a simulation.” To fully represent the Sun-Earth connection, SWMF must traverse 150 million kilometers of space, beginning 100 meters above the Sun’s surface (the corona) and ending 100 kilometers above the Earth (the ionosphere).

Following solar gas and particles through space, boxes in the computational mesh divide up to 15 times to cover scales down to 200 kilometers. Without employing this adaptive mesh refinement (AMR) technique, the simulation could not be run on today’s supercomputers. Even with AMR, the simulation will ultimately consume 500,000 processor-hours on NASA’s new Columbia supercomputer, an SGI Altix system at Ames Research Center in Moffett Field, CA. With a highly scalable code, “we can run faster than real time with 1,000 processors,” Gombosi said. His group is running the simulation using 512 processors, so it will take 40 days of computing time to model the 30 days of space weather.



In preliminary results from a simulation of the Halloween 2003 space storms, the Earth’s magnetosphere responds to an X-17.2 solar flare eruption on October 29. The visualization shows the last closed magnetic field lines, color-coded with pressure. The gray sphere is located at 3 Earth radii, while the maroon band on that sphere is a 100 nano-Pascals (nPa) pressure isosurface (Image credit: Darren De Zeeuw, University of Michigan).

Since the Halloween 2003 space storms were well observed from ground-based telescopes and orbiting spacecraft, there is a useful collection of data for comparison. Validating the simulation will help prepare SWMF as a community tool. Michigan is transferring the software to GSFC’s Community Coordinated Modeling Center and NOAA’s Space Environment Center in Boulder, CO. Researchers in these organizations will use SWMF codes for operational solar and space weather forecasting as well as scientific analysis.

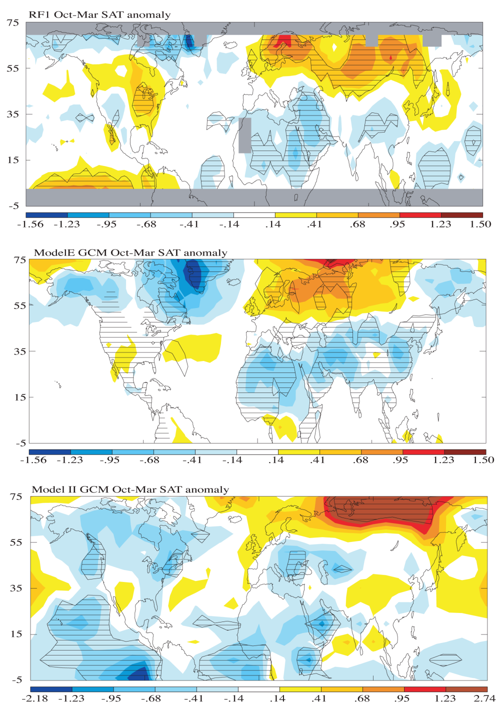
Gombosi and Michigan colleagues Darren De Zeeuw, Aaron Ridley, and Gabor Toth will be presenting SWMF and Halloween 2003 simulation results at the American Geophysical Union Fall 2004 Meeting, being held December 13–17 in San Francisco, CA.

http://ct.gsfc.nasa.gov
http://csem.engin.umich.edu

NCCS Aids GISS in Simulating Long-Term Climate Change

NCCS scientists are enhancing the Goddard Institute for Space Studies (GISS) ModelE climate model to take full advantage of the latest parallel computers and an emerging community software standard known as the Earth System Modeling Framework (ESMF).

ModelE represents the third generation of General Circulation Models (GCMs) developed at GISS in New York City. "Our main application is in understanding the development of long-term climate change and the extent it can be predicted," said Gavin Schmidt, GISS scientist and one of ModelE's developers. "This has led us over the years to first incorporate more physical elements, such as oceans and sea ice, and now more biogeochemical elements, such as atmospheric chemistry, aerosols, and dynamic vegetation, to allow more and more feedbacks to be simulated."



Visualizations show surface temperature anomalies during the cold season (October–March) following large tropical volcanic eruptions. The figure compares observations (top) with simulations by the GISS ModelE (middle) and previous-generation Model II (bottom) General Circulation Models. Among other advances, ModelE more closely matches cooling and warming patterns observed over Eurasia. Hatching indicates areas where the response is significant at the 95 percent confidence level (Image credit: D. Shindell and G. Faluvegi, Goddard Institute for Space Studies).

Recent uses of ModelE include simulating the 20th century climate for the Intergovernmental Panel on Climate Change and probing the effects of volcanic eruptions on global climate over 4 centuries, beginning in 1600.

GISS does most of their computing on the NCCS' Hewlett-Packard/Compaq AlphaServer SC45, where they consume hundreds of its 1,392 processors year round. ModelE's current OpenMP-based parallelization limits a model run to 1 shared-memory node, which has 4 processors. "Long runs that allow the fully coupled models to equilibrate can take hundreds of model years—and many months of real time," Schmidt said. Moreover, GISS runs at least 5 scenarios for each climate experiment, using different configurations and forcing conditions (e.g., swapping ocean models, with and without greenhouse gases). They typically have 60 model runs on the AlphaServer simultaneously.

To enable ModelE to run across multiple nodes, the NCCS has been modifying the parallelization from OpenMP to Message Passing Interface (MPI). MPI is the leading approach for interprocessor communications because it can call on the distributed memory used in many of today's computer architectures, including the AlphaServer. "A fully parallel model can run faster on a larger variety of systems," said Thomas Clune, lead for the NCCS' Advanced Software Technology Group. The NCCS ModelE team involves Clune, Rosalinda de Faintchtein of CSC, Hamid Oloso of AMTI, and William Putman of the NCCS.

Thus far, performance has improved from 2.7x speed-up on 4 processors using OpenMP to 5.9x speed-up on 8 processors using MPI. Clune expects that ModelE will be able to exploit as many as 45 processors when using 2- by 2.5-degree resolution. In addition to routinely running at this higher resolution, Schmidt anticipates "simulations with… more sophisticated parameterizations" as well as "more extensive testing and longer runs."

Another possibility that MPI raises is incorporating parallel model components from other organizations. Turning promise into reality is ESMF, a standard for coupling weather and climate model components being developed under NASA's Computational Technologies Project. "In our second phase, we will be converting key aspects of ModelE to be ESMF-compliant," Clune said. "There are physical quantities such as temperature, pressure, and humidity that are spatially dependent. We wrap these up into ESMF fields, which are meta-information, what ESMF needs to know so components can be coupled."

A component of particular interest is the finite-volume dynamical core (FVCORE) used in the GSFC Global Modeling and Assimilation Office's fvGCM and new GEOS-5 GCM. "The dynamics of the atmosphere are one of the absolutely key parts of any GCM," Schmidt said. "We must therefore be able to test different formulations of these fundamental equations, of which FVCORE is one." FVCORE has been prepared as an ESMF component, and the NCCS team's first goal is making ModelE ESMF-compliant enough to attach FVCORE to it.

In working with ModelE, the NCCS takes an atypical approach. "We are parallelizing the model while GISS developers work on science aspects of the code," Clune explained. The NCCS insulates GISS by maintaining two separate code repositories, one for development at GSFC and one for production at GISS; the staff periodically merges the repositories. "Usually, scientists hand over a code to an optimization expert who goes away for six months, and then they try to integrate it back in. Frequently, it gets abandoned. We always provide GISS with a working version that incorporates their latest science improvements. It is more work on our part, but it ensures that the product has long-term value for GISS," Clune said.

http://www.giss.nasa.gov/tools/modelE/

Education and Public Outreach

VSEP Students Contribute to Computer-Related Research

The Visiting Student Enrichment Program (VSEP) provides computer-related work experiences to students from universities, colleges, and high schools throughout the United States. VSEP is managed by Marilyn Mack of the ESDCD's Science Communications Technology Branch (SCTB). This summer the program matched 15 students with mentors in 12 GSFC branches, including the 3 branches of the ESDCD. A selection of 2004 projects follows.

VSEP Class of 2004 (Image credit: Debora McCallum).

Thomas Clune of the NCCS and Michael Witkowski of AMTI mentored Angie Albers (University of Oklahoma), who implemented a dynamic web-based application enhancing reporting and user service requests for the NCCS user community.

Andrea MacLeod (Texas A&M University Corpus Christi) assisted Pat Gary (ESDCD) and members of the SCTB in testing experimental modifications to the TCP congestion control scheme in an attempt to utilize bandwidth more efficiently when transmitting large amounts of data over long-distance networks.

Hamid Oloso of AMTI and Clune mentored Ghalib Bello (Whittier College) in profiling and analyzing performance of the Global Modeling Initiative (GMI) code. They also created a parallel implementation of the PENELOPE (PENetration and Energy LOss of Positrons and Electrons in matter) Monte Carlo photon/electron transport simulation package for Tim Burbine of the National Research Council in the Astrochemistry Branch of the Laboratory for Extraterrestrial Physics.

Oloso and Witkowski worked with Babatunde Azeez (Texas A&M University) to develop Perl programs to more efficiently process the NCCS users' database. They designed a program to extract high-performance computing system resource usage and accounting information and a high-quality interactive web interface for querying and generating reports for statistical analysis based on the processed database.

Jacqueline LeMoigne of the Applied Information Sciences Branch mentored Nir Kalush (University of Maryland), who assisted in testing image registration algorithms and translating an existing algorithm from MATLAB to C.

Susan Hoban of the Earth Sciences Directorate mentored Natalie Vershov (Beth Tfiloh High School), who designed examples for the NASA Explorer Schools "Return to the Moon" Challenge research project and created a web-based repository of examples for the project's participants.

Christa Peters-Lidard of the Hydrological Sciences Branch mentored Peter Anderson (Macalester College) as he designed a streamlined data management system for the Land Information System (LIS) cluster to increase the cluster's efficiency and make it usable for constant real-time simulations.

http://vsep.gsfc.nasa.gov

HPC Summer School Celebrates Its 12th Year

From July 12–30, 2004, ESDCD's 12th Annual Summer School for High-Performance Computational (HPC) Earth and Space Science hosted 15 graduate students from 12 universities, including the University of California, Brown University, Utah State University, the University of Washington, Drexel University, Johns Hopkins University, and the University of Maryland, among others. The students received hands-on parallel supercomputer training lectures on topics ranging from parallel languages, software frameworks and developing good software practices for modern scientific codes, to numerical techniques in fluid dynamics, particle methods, magneto-hydrodynamics, adaptive mesh refinement, and atmospheric data assimilation. The students also gave presentations on their thesis research interests during the course of the program.

This year the school also deployed its first "wireless classroom," devised by the ESDCD to enable computer training to move away from the restrictions of specialized classrooms with fixed terminals, allowing students to use their own environments. As with any new technology, the wireless classroom required some initial finessing, but the network and system administrators and User Services Group were there to support the school. "The NCCS staff did a tremendous job in getting things going and keeping them going," said Anil Deane (University of Maryland/GSFC), Director of the Summer School.

Photos from the HPC Summer School (Image credits: Anil Deane, University of Maryland/GSFC).

The HPC Summer School is jointly sponsored by the Earth Sciences Directorate and ESDCD and administered by UMBC. It was developed over the past decade by the ESTO Computational Technologies Project, which has ended.

http://ct.gsfc.nasa.gov/summer_school.html

ESDCD Updates

Discovery of Interstellar Sugar Is Key to Investigating Our Molecular Origins

When people take a sabbatical, they often joke that they are going to ponder the meaning of life. In 1998, Jan M. Hollis, a senior scientist in the ESDCD, chose a different focus for his sabbatical. He decided to study the molecular origin of life in the universe. “There are some researchers, like those in the SETI effort, who hope that E.T. phones home,” Hollis says. “What I am doing is investigating whether the conditions for the molecular origins of life as we know it exist in space.” His recent discoveries have provided new clues to this age-old mystery and offer support for an alternate theory about how life began on our planet.

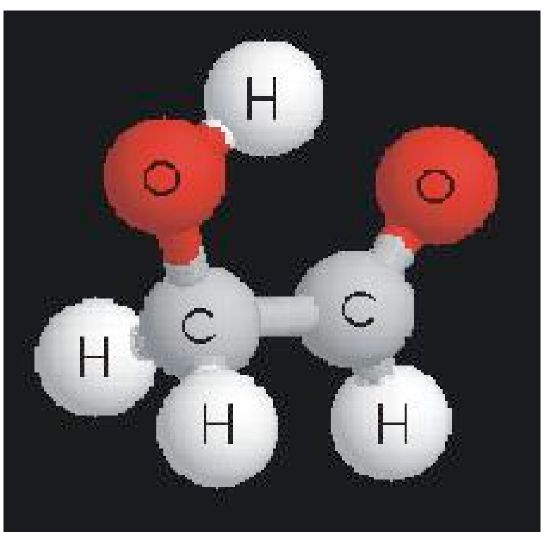
Scientists generally hypothesize that life must have begun with the evolution of simple molecules into the more complex sugars, amino acids, and other prebiotic molecules that are regarded as life's molecular building blocks—the so-called biomolecules. Hollis, an astrophysicist, decided to conduct a search in space for these key molecules that are necessary for the origin of life. He concluded that the most likely class of molecules to search for in our galaxy would be simple sugars, in the giant molecular clouds from which stars and planets form. Because sugars are associated with both metabolism and the genetic code, two of the most basic aspects of life, Hollis rationalized that the discovery of any sugar in space would increase the likelihood that life may exist elsewhere in our galaxy.

Hollis chose the simplest monosaccharide sugar, glycolaldehyde, for the search. A molecule comprised of 2 carbon, 2 oxygen, and 4 hydrogen atoms, glycolaldehyde is an important biomarker that can react to form glycolaldehyde phosphates and more complex sugars such as ribose (which contains 5 carbon atoms). Ribose is a building block of nucleic acids such as RNA and DNA—the carriers of the genetic code in living organisms.

Hollis formed an observing team, which included Frank Lovas (University of Illinois) and Phil Jewell (National Radio Astronomy Observatory), wrote a competitive proposal for time on a 12-meter-diameter radio telescope, and waited for more than a year before the experiment was finally scheduled. In 2000 the research efforts of Hollis' team were rewarded. In the star-forming region near the center of our galaxy, at a position known as SgrB2 (N-LMH), they found glycolaldehyde—the first evidence of an interstellar sugar molecule.

Molecules rotate end-for-end, and as they change from one rotational energy state to another, they emit radio waves at precise frequencies. The "family" of radio frequencies emitted by a molecule forms a unique set of "fingerprints" that scientists can use to identify that particular molecule. Hollis' team detected glycolaldehyde by observing faint radio emission in the 71 to 103 GHz range from a large ensemble of the molecules in the interstellar cloud. However, while glycolaldehyde was identified, there was no information in the original experiment regarding its spatial extent.

The National Radio Astronomy Observatory's (NRAO) 12 Meter Telescope was used by Jan Hollis (ESDCD), Frank Lovas (University of Illinois), and Phil Jewell (NRAO) to detect the sugar molecule glycolaldehyde in an interstellar molecular cloud (Photo credit: NRAO).



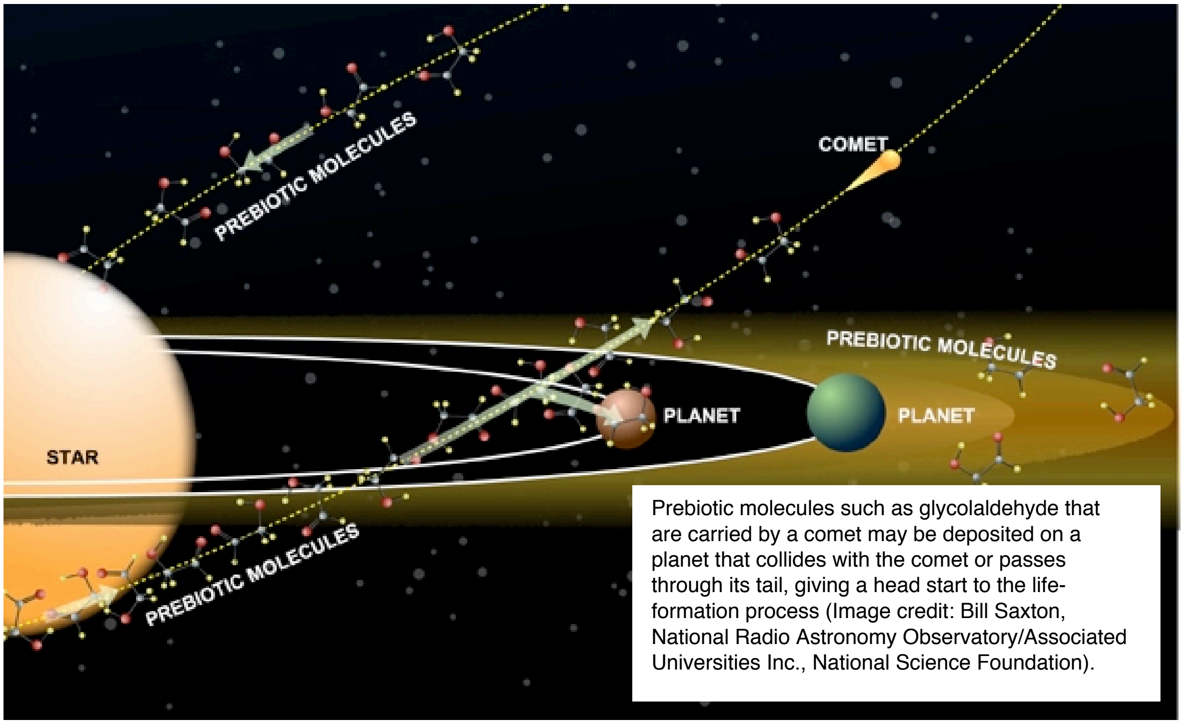
The chemical structure of glycolaldehyde. Atoms and connecting bond lengths are not to scale (Image credit: National Radio Astronomy Observatory).

In 2001 Hollis and collaborators conducted a second experiment using a multiple radio telescope system, called an interferometer, which permits spatial imaging of molecular emission. The interferometer experiment showed that, unlike most other large interstellar molecules, glycolaldehyde is not confined to the hot core of SgrB2 (N-LMH). This hot core, known as the Large Molecule Heimat or Homeland (LMH), has a spatial diameter of only 5 arcseconds on the sky and a characteristic temperature of 200 Kelvin (K), which is actually quite hot for interstellar molecules since all molecular motion stops at 0 K. Comparison of the single-antenna data and the interferometer data indicated that the glycolaldehyde gas has a temperature of about 50 K and a much larger spatial scale at least 12 times the size of the LMH. Moreover, the large spatial extent of glycolaldehydes spawned the mapping of simpler aldehydes, which indicates that these molecules are very widespread.

Hollis and collaborators again probed the same interstellar cloud in 2002 and discovered the sugar alcohol of glycolaldehyde known as ethylene glycol, a 10-atom species that is the primary ingredient of automobile antifreeze. The importance of finding 2 sugar-related molecular species together indicates that the synthesis of more complex sugars is likely occurring in interstellar clouds. Hollis and his team further discovered in 2003 that the source containing these interstellar sugar-related molecules is centered on a star-forming region that contains enough mass to make approximately 2,600 new stars as massive as our Sun.

Most recently, in April 2004, Hollis and collaborators again probed interstellar glycolaldehyde using a new single-antenna, 100-meter-diameter telescope with a collecting area of more than 2 acres and receivers operating at lower frequencies in the range of 13 to 22 GHz. The results were surprising because the emission was strong relative to the original detection and the gas has an extremely low temperature—only 8 K. This result contrasted with the 50 K reading in the original observations, which used higher frequencies. "We expected the glycolaldehyde molecules to exist at the same temperature, but we were wrong," Hollis says. Using these new glycolaldehyde results along with results of other investigators, Hollis and his team have a much clearer picture of what produces the biomolecules they have studied.

Such large molecules are first produced on surfaces of dust grains when an interstellar cloud of gas and dust experiences a shock wave. This can easily happen during the collapse phase of star formation when material collides. The dust grains are typically about a micrometer in size and are coated with a variety of ices that contain simple molecules, which can include water, formaldehyde, methane, ammonia, carbon dioxide, and methanol. The resulting shock of the colliding material provides the energy re-



Prebiotic molecules such as glycolaldehyde that are carried by a comet may be deposited on a planet that collides with the comet or passes through its tail, giving a head start to the life-formation process (Image credit: Bill Saxton, National Radio Astronomy Observatory/Associated Universities Inc., National Science Foundation).

quired to produce glycolaldehyde from simpler molecular species that reside on the grains. In turn, the ethylene glycol is produced from the glycolaldehyde when 2 hydrogen atoms successively react with a glycolaldehyde molecule. The shock also serves to free molecules from the dust grains, distributing glycolaldehyde and ethylene glycol into the gas on a widespread spatial scale. After the shock wave passes, the glycolaldehyde and ethylene glycol that have been released into the gas phase rapidly cools, forming the so-called post-shock gas.

Sugar formation, as with much of the complex molecular chemistry in space, occurs in the solid phase on or in a variety of ices that coat interstellar grains. Most terrestrial chemistry occurs in the liquid phase, primarily with water, thus the widely accepted theory that life on Earth began in a "primordial soup." While these two chemistry scenarios are very different, the end results can be very similar. "One thing is clear—a lot of prebiotic chemistry occurs in an interstellar cloud long before that cloud collapses to form a new solar system with a central star and orbiting planets and comets," Hollis says. "This suggests that the molecular building blocks necessary for life to arise on a newly formed planet get a head start in interstellar clouds." Planetary formation is such a hot process that biomolecules would be destroyed in the process. However, comets are formed in a much colder process within the same interstellar cloud and are frequent space visitors that can supply fresh molecules to a new planet that has finally cooled down. Supporting the notion of complementary theories for the molecular origins of life, Hollis maintains, "Many of the interstellar molecules discovered to date are the same species detected in laboratory experiments specifically designed to synthesize prebiotic molecules. This fact suggests a universal prebiotic chemistry."